FOIL SUPPORT STRUCTURE
FOR LARGE ELECTRON GUNS

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Abstract:

This paper describes a novel support structure for a vacuum diode used to pump a gaseous laser with an electron beam. Conventional support structures are designed to hold a foil flat and rigid. This new structure takes advantage of the significantly greater strength of metals in pure tension, utilizing curved shapes for both foil and support structure. The shape of the foil is comparable to the skin of a balloon, and the shape of the support structure is comparable to the cables of a suspension bridge. This design allows a significant reduction in foil thickness and support structure mass, resulting in a lower electron-beam loss between diode and laser gas. In addition, the foil is pre-formed in the support structure at pressures higher than operating pressure. Therefore, the foil is operated far from the yield point. Increased reliability is anticipated.

Introduction:

High-power gas lasers utilize electron-beam pumping. A foil is required to separate the vacuum diode from the laser gas, and a foil-support structure is required to allow a thin foil to span a large-area diode. High electron-beam transmission through the foil and support structure is a critical parameter in the design of efficient laser systems.

Earlier Technology:

Previous foil support structures for large area diodes have been designed using traditional skin stress theory based on aircraft skin designs. This design philosophy is based on a rigid beam support structure with beams spaced closely enough to keep the skin surface essentially flat. Skin thickness and structure geometry were designed to keep the stresses in all components below the yield point. This design philosophy favored very high tensile strength materials.

The typical foil support structure has been a 'hibachi' type structure machined from a solid thick plate of high strength metal. Geometric open areas in the range of 80% are typical. Since the electron beam spirals as it passes through the support structure, the depth of the support beams intercept a significant portion of the beam. Effectively, the open area becomes significantly less than the geometric open area because of the shadow caused by the beam depth.

Foil support structures with large open areas will usually allow the foil to stretch a small amount. This effect is indicated by the dimples or puckering that is often seen in a foil after it has been used. The fact that any stretching has occurred shows that the foil has been stressed beyond its elastic limit. Since foils have generally not been proof pressured to pressures significantly higher than their working pressure, this stretching further indicates that such foils have been at their yield stress during service.

Early Technology Shortcomings Major shortcomings of the early technology have been foil failures due to operation at the yield point and the loss of a significant portion of the electron beam into the support structure. Both of these shortcomings have been addressed in this new design.

New Support Structure

The new support structure is a radical departure from conventional designs. Material is selected for its ductility, is used in pure tension, and is allowed to stretch into a geometry with a small radius of curvature that can support the pressure. Since the material is being used in pure tension, rather than beam bending, it makes a much more efficient structure. Compare the basic design difference to the difference between a suspension bridge and a conventional girder bridge. The suspension bridge is in tension, and for a given span requires much less material to carry an equivalent load.

In addition to requiring less material, this new design has a higher geometric open area (greater than 90%, depending on pressure) and has minimal beam interception to a spiraling beam because it has a very shallow depth compared to the typical hibachi structure.

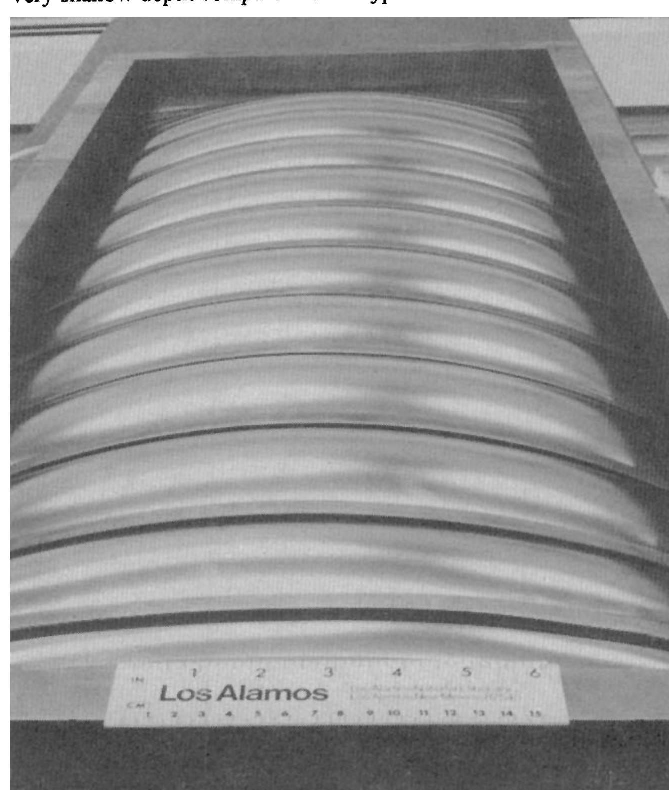

Figure 1 First Prototype

The first prototype of this design (Figure 1) was fabricated with a solid steel frame and pre-formed steel tension rods. The tension rods were rolled to a curvature that was designed to withstand a proof/preform pressure twice the nominal working pressure of 750 Torr. The rods were spaced at a distance that was calculated to

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This paper describes a novel support structure for a vacuum diode used to pump a gaseous laser with an electron beam. Conventional support structures are designed to hold a foil flat and rigid. This new structure takes advantage of the significantly greater strength of metals in pure tension, utilizing curved shapes for both foil and support structure. The shape of the foil is comparable to the skin of a balloon, and the shape of the support structure is comparable to the cables of a suspension bridge. This design allows a significant reduction in foil thickness and support structure mass, resulting in a lower electron-beam loss between diode and laser gas. In addition, the foil is pre-formed in the support structure at pressures higher than operating pressure. Therefore, the foil is operated far from the yield point. Increased reliability is anticipated.

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allow the 1 mil Inconel foil to stretch approximately 12% between the rods at the proof/preform pressure. Several pressure cycles of 1500 Torr have been successfully placed on the 1 mil Inconel foil in the prototype. At the 1500 Torr pressure, the foil stretched into the support rods as expected and maintained its shape without wrinkles after the pressure was removed.

After the success with the pre-formed rods, a simpler design based on annealed wire supports was conceived and tested (Figure 2). This simpler design was built on a smaller scale than the original prototype and consequently was designed for a higher proof/preform pressure. The fixture was constructed from a plate of aluminum 3/8 inch thick by 5 inches wide by 14 inches long with a clamp bar frame of 3/8 inch by 1 inch aluminum around the perimeter. The plate and frame were then drilled with 9/32" diameter holes spaced at 1 inch intervals at the ends, and .700 inch intervals along the long edges. The .700 spacing was selected to match the spacing of wires that was calculated to hold 150 psi proof/preform pressure with a nominal working pressure of 75 psi. Load distribution sheets of 1/32" by 1" aluminum were also drilled to match the .700 hole pattern. Wires were cut from a roll of annealed .080" diameter steel wire to 5 inch length and straightened. Additional spacer wires approximately 1/2 inch long were also cut.

Assembly consisted of first placing a strip of 1 inch transfer adhesive around the perimeter of the plate and then attaching a sheet of 1 mil Inconel foil to the plate with this adhesive. Holes were cut in the Inconel with an X-acto knife to match the holes in the plate. The two short aluminum bars were then bolted to the plate with 1/4 inch screws and nuts. Next, the load distribution sheets were attached to the foil with the .700 interval holes lined up using transfer adhesive. A strip of transfer adhesive was then placed on the load distribution sheets. Support wires and spacer wires were then placed on the adhesive strip as shown in Figure 2. The two long clamp bars were then placed on the wires and the entire assembly was bolted together with 1/4 inch screws and nuts. Pressure is transferred from the clamp bars through the spacer wires and load distribution sheets to the foil in order to prevent foil slippage. A nitrogen gas bottle and regulator were attached to a tapped hole in the back of the plate, and a precision pressure gage was attached to a second hole in the plate. Increasing gas pressure between the foil and the plate caused the foil to stretch against the wire supports and then stretch the wire supports into curved shapes. The pressure was slowly increased to 150 psi. Wire diameter and spacing were designed to support a proof/preform pressure of 150 psi. Unfortunately, the foil ruptured at 150 psi due to surface irregularities on the support wires. However, the test was deemed a success because the foil had taken the expected shape and had stretched the wires as expected prior to rupturing.

A full size support structure for the Mercury A2 KrF amplifier at Los Alamos has been designed for a working pressure of 700 Torr and a proof/preform pressure of 1400 Torr. (See Figure 3) The structure is comprised of a simple stainless steel frame with annealed stainless steel wires placed parallel to each other across

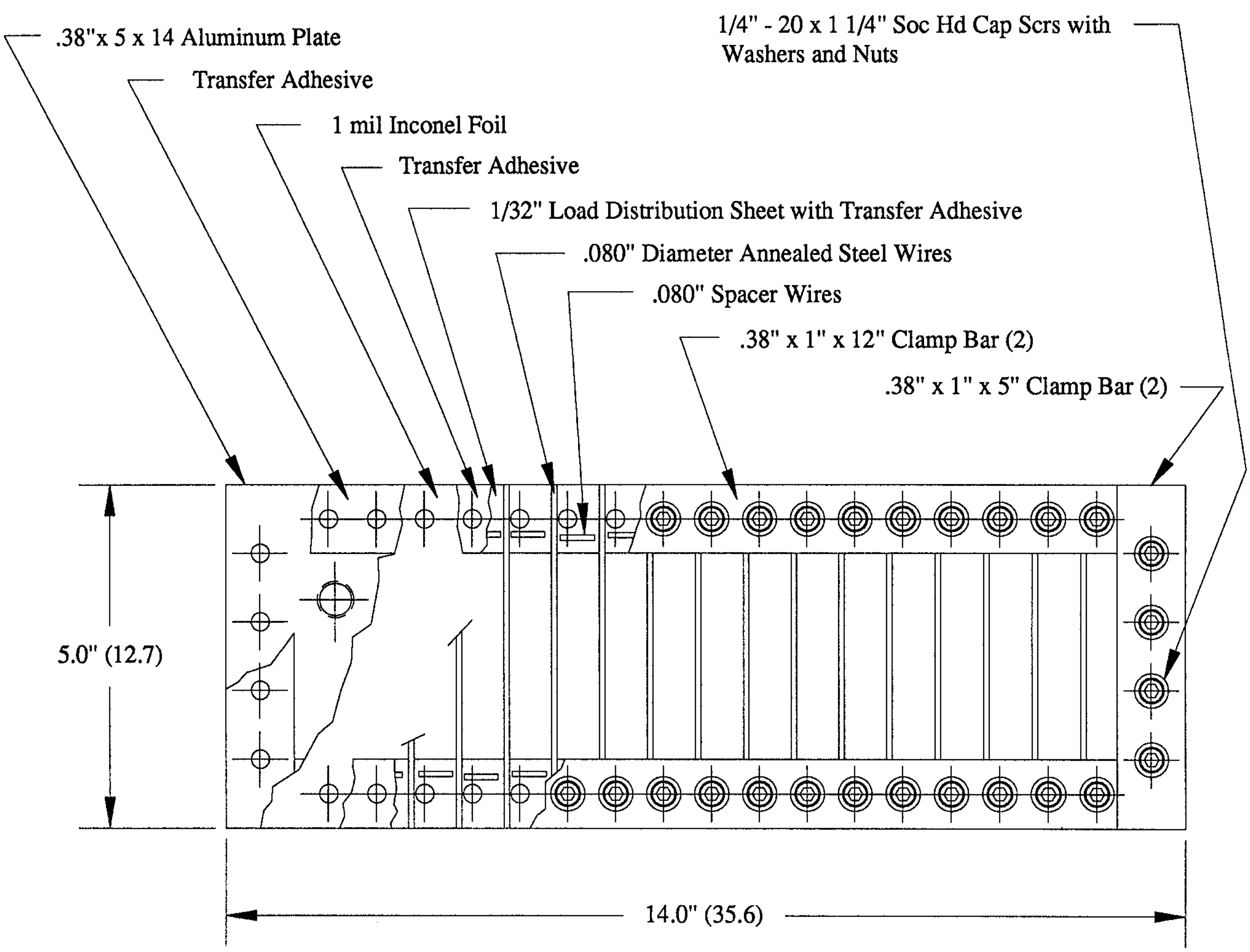

Figure 2 Second Prototype

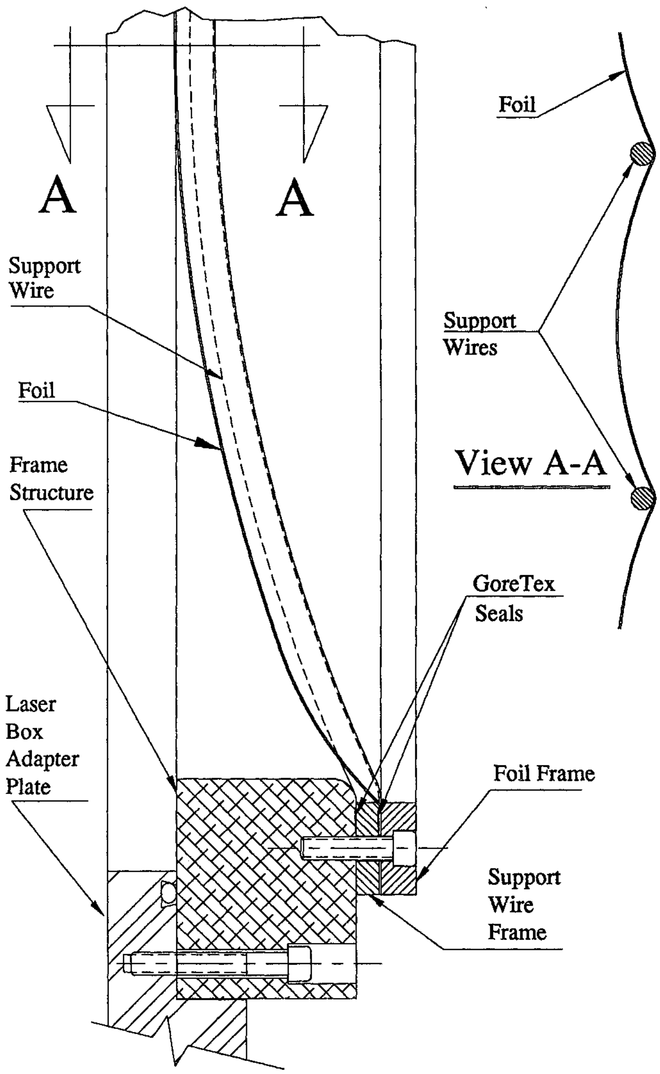

Figure 3
Mercury A2 Amplifier Foil Support

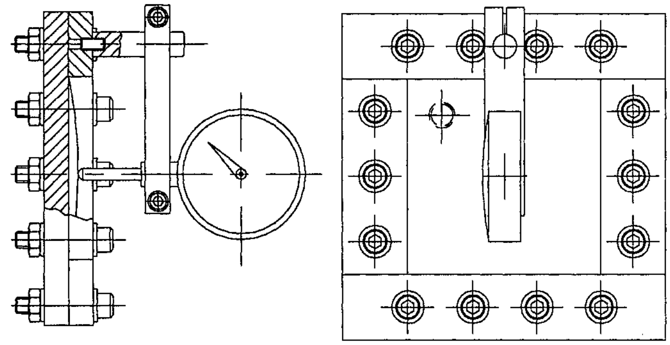

Figure 4 Foil Test Fixture

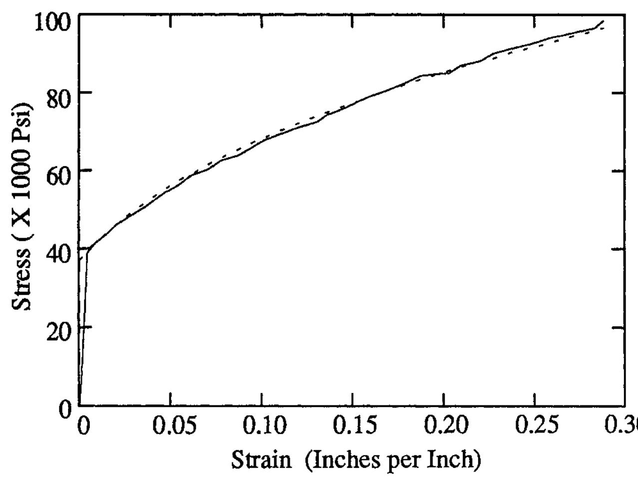

Figure 5 Stress/Strain Curve

the narrow width of the electron beam window. These wires are welded to the inner perimeter of the frame at the spacing required to support the proof/preform pressure. Foil and a foil frame is laid against the support wires, clamped in place with a cover plate, and pressurized to the proof/preform pressure. Since there is no room for 'O' rings, seals are made with expanded Teflon rope such as Goretex. The pressure causes the foil to first stretch between the support rods and then stretch the rods into a circular segment.

At the proof/preform pressure, the foil and the rods are stretched to some fraction of their total elongation capabilities, and have taken a circular shape that allows them to support the proof/preform pressure. Since the supports and foil have been stretched beyond the yield point by the proof/preform pressure, the working pressure will be well below the yield point and foil failures will be minimized.

Construction costs of this design are a fraction of conventional hibachi structures because there is very little machining. The following example uses .001 inch thick Inconel 600 foil and has a support structure fabricated from stock materials of 1/4" x 1" 304 SS bar stock and 1/4" dia 304 SS wire. Both of these are readily available materials and their fabrication is relatively simple.

Sample Calculations

First, the foil to be used (1 mil annealed Inconel 600) was tested in a simple fixture to provide a stress/strain curve. This fixture (See Figure 4) is a simplified version of a fixture described and used by Hill[1]. The foil is stretched bi-axially, just as it is in the support structure. The result of the test is the stress/strain curve shown in Figure 5. The solid line represents empirical data from 36 different pressures and deflections measured on the test fixture. The dashed line represents the curve of the equation

$$S = A * (B + \varepsilon)^n$$

where S = Stress,
ε = Strain,
A = 150,000 psi,
B = 0.025, and
n = 0.38

with A, B, and n as constants selected for the best curve fit.

We will design the support structure using 80% of the ultimate stress as the design proof/preform stress. To keep the working stress well below material yield, we will multiply the working pressure by two to get the proof/preform pressure. For instance, the A2 Amplifier will use KrF laser gas at a nominal pressure of 600 Torr with a pressure jump of about 100 Torr. Therefore the working pressure is about 700 Torr, and the proof/preform pressure will be 1400 Torr. This is about 27 psid (psi differential).

Uni-axial hoop stress in a cylinder under pressure is

$$S = pr/t$$

where S is the material stress in psi,
p is the internal pressure in psi,
r is the radius of curvature of the cylinder in inches, and
t is the wall thickness in inches.

Then, we can solve for the radius of curvature as

$$r = St/p.$$

Bulge tests done in the test fixture have shown the ultimate tensile stress of our 1 mil Inconel foil (See Figure 5) to be about 95,000 psi. Therefore, our design proof/preform stress will be 76,000 psi.

So, for 1 mil Inconel, since the proof/preform stress is 76,000 psi; and the proof/preform pressure is 27 psi, our design radius of curvature is:

$$r = 76{,}000 * 0.001 / 27 = 2.81 \text{ in.}$$

From the stress/strain curve, we can determine the elongation of the foil. It shows that Inconel has an elongation of approximately 15% at 76,000 psi.

Next, we need to determine if the system geometry can tolerate the foil elongation at the proof/preform pressure. The A2 Amplifier has a vertical aperture of 16 inches with a nominal e-beam drift space between the anode and the foil of slightly more than 4.5 inches, so the depression in the center of the foil will be constrained to less than four inches. For an aperture of 16 inches, with an elongation of 15%, the depression at the center would be 3.89 inches. Therefore, we can accept the 15% stretch of the Inconel foil in the 16" direction between the frame structure members. The radius of curvature of the foil between the 16" frame members would be about 10.2 inches for the 15% stretch. Our previous calculation showed that the maximum radius of curvature for the 1 mil Inconel foil at 27 psi is 2.81 inches. Therefore support wires will be required to carry the tensile load in the foil between the 16" members. Spacing between the support wires is determined from the elongation and the radius of curvature. For an elongation of 15% at a radius of curvature of 2.81 inches, the spacing between supports needs to be no greater than 4.4 inches. Since our open aperture is 84 inches long, we can divide by 20 to get a nice even wire spacing of 4.2". Twenty wires will be spaced 4.2 inches apart with 2.1 inches at each end. This spacing will give us an elongation of about 13% with a 2.81 inch radius of curvature.

The depression between support wires at 4.2" spacing and 13% stretch will be 0.945". We have already noted that the foil depression between the 16" inner edges of the frame structure will be 3.89" at 15% stretch. Therefore, the depression at the center of the support wires will need to be 3.89 - .945 = 2.945". Geometry calculations show that this stretches the support wires about 9% and forms a radius of curvature of about 12.1 inches.

Support wire stress is calculated as the hoop stress of the cylinder between supports divided by the support cross section.

Then, $S = prd/A$

where, S = Stress in psi
p = pressure in psi
r = radius of curvature of the support wires
d = distance between support wires, and
A = cross section area of support wires.

Solving for the wire area gives

$$A = prd/S$$

We selected annealed 304 SS for the foil support material. At an elongation of 8%, 304 SS has a yield strength of about 38,000 psi. Therefore, the following cross section would be required on each wire.

$$A = (27 * 12.1 * 4.2) / 38{,}000 = 0.036 \text{ in}^2$$

Since the cross section shrinks as the length elongates, the original cross section of the wire will need to be:

$$A = 0.036 / 0.92 = 0.039 \text{ in}^2$$

This is equivalent to a wire diameter of 0.223. Since .25 dia is standard material, we will use it for the design. This larger wire size will then give us slightly less stretch across the 16" support width. Since we have an aperture width of 84 inches obscured by twenty .250 diameter wires, we have a geometric open fraction of

$$(84 - (20 \times .25))/84 = .94$$

or 94%.

Conclusion

Testing a small sample of foil in a bulge test fixture gives an accurate determination of its stress-strain curve. We have designed a support structure that takes advantage of the experimentally determined characteristics of the material to optimize e-beam transmission through the foil and support structure. We plan to field and test the new foil support structure later this year on the A2 krypton-fluoride laser.

References

[1] R. Hill, "A Theory of the Plastic Bulging of a Metal Diaphragm by Lateral Pressure" Phil Mag, 1950, (Ser 7), ch 41, pp 1133-1142